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Musicianship facilitates the processing of Western music chords—An ERP and behavioral study

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ABSTRACT

The present study addressed the effects of musicianship on neural and behavioral discrimination of Western music chords. In abstract oddball paradigms, minor chords and inverted major chords were presented in the context of major chords to musician and non-musician participants in a passive listening task (with EEG recordings) and in an active discrimination task. Both sinusoidal sounds and harmonically rich piano sounds were used. Musicians outperformed non-musicians in the discrimination task. Change-related mismatch negativity (MMN) was evoked to minor and inverted major chords in musicians only, and N1 amplitude was larger in musicians than non-musicians. While MMN was absent in non-musicians, both groups showed decreased N1 in response to minor compared to major chords. The results indicate that processing of complex musical stimuli is enhanced in musicians both behaviorally and neurally, but that major–minor chord categorization is present to some extent also in the absence of music training.

1. Introduction

Musicianship is associated with structural and functional differences in the brain when compared with non-musicians (see Münte, Altenmüller, and Jäncke (2002), Herholz and Zatorre (2012), and Moreno and Bidelman (2014)). According to evidence currently available, these differences can be attributed to the extensive training and not, for example, to innate differences between musicians and non-musicians. This evidence includes follow-up studies of children who begin instrument training (Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006; Hyde et al., 2009; Putkinen, Tervaniemi, Saarikivi, Ojala, & Huotilainen, 2014; Schlaug, Norton, Overy, & Winner, 2005), studies of non-musician adults demonstrating short-term training effects (Lappe, Herholz, Trainor, & Pantev, 2008; Draganova, Wollbrink, Schulz, Okamoto, & Pantev, 2009), and studies showing that in musicians, the extent of brain changes correlates with years of instrument training (Pantev et al., 1998).

In the auditory domain, enhanced gray matter volume and density are seen in the auditory cortices of musicians (Schneider et al., 2002; Sluming et al., 2002; Pantev et al., 1998; Gaser & Schlaug, 2003; Shahin, Bosnyak, Trainor, & Roberts, 2003; James et al., 2014). Together with these structural findings, changes in the auditory event-related potentials (ERPs) of the electroencephalogram (EEG) suggest expanded activation areas, larger number of neurons, greater synchronization, or faster connectivity in the brain of musicians. For example the N1 component that reflects basic auditory processing and is modified by physical stimulus features (Näätänen & Picton, 1987) shows enhanced amplitudes and/or shorter latencies in musicians compared to non-musicians (Pantev et al., 1998; Pantev, Roberts, Schulz, Engelien, & Ross, 2001b; Shahin et al., 2003; Kaganovich et al., 2013). Similarly, the mismatch negativity (MMN), an index of pre-attentive auditory discrimination (Näätänen, Gaillard, & Mäntysalo, 1978; Näätänen, Paavilainen, Rinne, & Alho, 2007), is modified by musicianship (Koelsch, Schröger, & Tervaniemi, 1999; Rüsseler, Altenmüller, Nager, Kohlmetz, & Münte, 2001; van Zuijen, Sussman, Winkler, Näätänen, & Tervaniemi, 2005). Enhanced ERPs are seen in musicians especially when the sounds are complex (Kaganovich et al. (2013); but for contrasting results see Nikjeh, Lister, and Frisch (2009)) or music-related (Pantev et al., 1998, 2001b, 2003; Pantev, Engelien, Candia, & Elbert, 2001a; Koelsch et al., 1999; Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004, 2005).

Despite their central role in Western music, the neural basis of Western music chord processing and the effects of musicianship on it have not been extensively studied (for previous evidence, see Koelsch et al. (1999), Brattico et al. (2009), and Tervaniemi, Sanneman, Nöyränen, Salonen, and Pihko (2011)). The present study is part of a large project established to systematically

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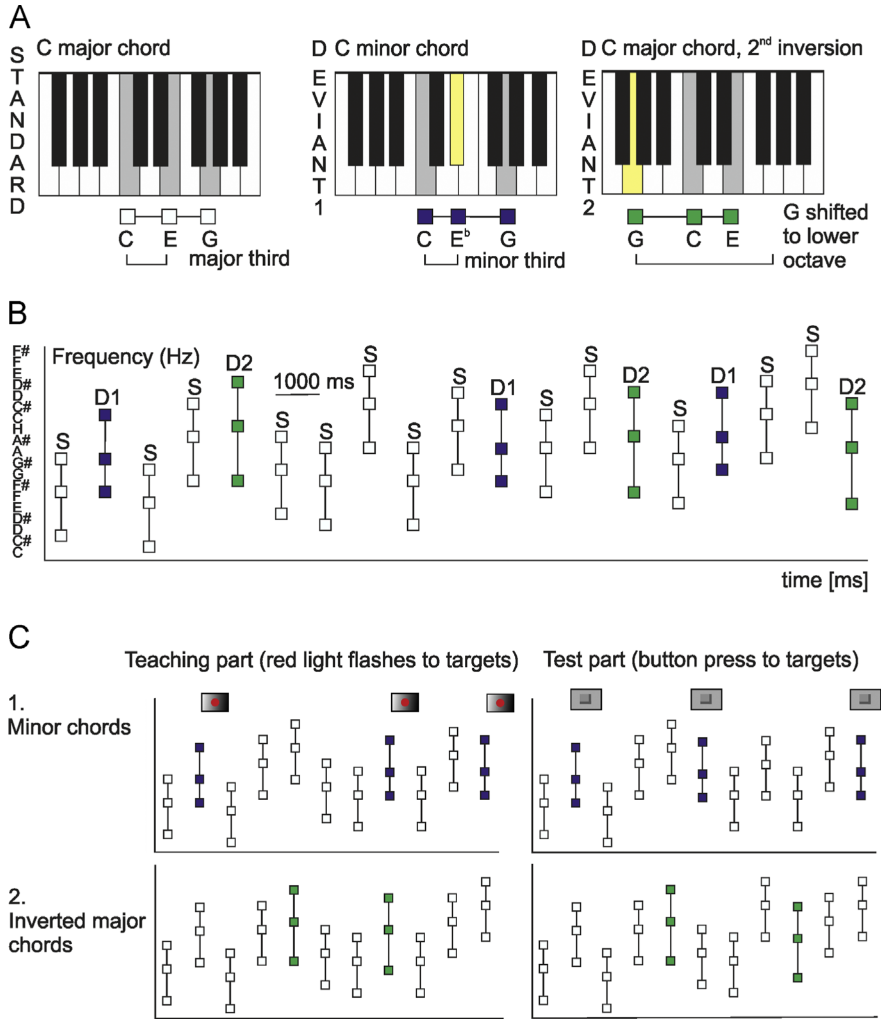

Fig. 1. A. Examples of the experimental stimuli in EEG paradigms and behavioral chord detection task. Chord types and their interval structures are illustrated with C-major (standard, major chord), C-minor (deviant, minor chord) and 2nd inversion of C-major (deviant, 2nd inversion of major chord) on a piano keyboard. B. EEG paradigm with major chords (white) transposed to 12 frequency levels presented as standards and minor chords (blue) and 2nd inversions of major chords (green) both transposed to 3 frequency levels presented as deviants. C. Behavioral chord detection task paradigms with major chords presented as standards and either minor chords or 2nd inversions of major chords presented as deviants.

investigate the effects of musicianship on the auditory cortical processing of Western music chords as reflected by the ERPs in participants at various age groups (adults, adolescents, and newborns; Virtala et al., 2011; Virtala, Huotilainen, Putkinen, Makkonen, & Tervaniemi, 2012, Virtala, Huotilainen, Partanen, Fellman, & Tervaniemi, 2013). The specific aim of the present study in this context was to first, investigate the effect of musical expertise on chord processing and, second, to improve the ecological validity of our paradigm by introducing harmonically rich piano sounds in addition to sinusoidal sounds to the participants. Additionally, for the first time, the behavioral detection of chord types and the relationship of ERPs to behavioral performance were studied.

Interval structure, the mutual relationships between a chord's notes, defines the chord's identity in music, making it for example a major or a minor chord (interval structures of major and minor chords are illustrated in Fig. 1A). Similarly, certain interval structures make the chords sound dissonant or mistuned. There is evidence that short-term training may lead to increased accuracy in behavioral discrimination of chords in non-musicians (Oechslin, Läge, & Vitouch, 2012), suggesting that explicit training can facilitate their processing. Neurally, there is evidence of musicians' superior processing of small frequency changes related to mistuning in chords, as reflected by enhanced MMNs (Koelsch et al., 1999). In a study by Brattico et al. (2009), musicians had larger MMN-responses than non-musicians to dissonant and mistuned chords in the context of A major chords. While MMN was also elicited by A minor chords in the context of A major chords, there was no difference between musicians and non-musicians in its strength, suggesting that even non-musicians are highly capable of major–minor categorization. In contrast, another study showed that MMNs to C minor chords in the context of C major chords were smaller in non-musicians than musicians or musically competent participants (Tervaniemi et al., 2011; for comparable music training effects in children see Putkinen et al., 2014). However, the aforementioned studies introduced single examples of major and minor chords in the paradigm. The obvious frequency differences between them could have elicited the MMNs even in the absence of mode differences (major vs. minor) between the standard and deviant stimuli. Thus, the questions whether non-musicians demonstrate pre-attentive neural discrimination of different chord types in general and major vs. minor chords in particular, and whether this neural discrimination is superior in musicians, were left open by previous work.

These questions were examined in prior work of the authors, together with the introduction of a new well-controlled MMN paradigm (Virtala et al., 2011, 2012, 2013). In the paradigm, Western music chord types transposed to several frequency levels were presented in random order. Because of the wide frequency spectrum of transpositions, each note in the deviant minor chords was also present in some of the standard major chords. Thus, the only deviating factor between the chord types was their interval structure, the property that separates the chord types by definition. In addition to the minor chord, an inverted major chord (2nd inversion, illustrated in Fig. 1A) was presented as a deviant, in order to include a deviant type that had a deviating interval structure but the same mode as the standard major chord. When introduced with this new paradigm, non-musician adults demonstrated MMNs to minor chords in the context of major chords (Virtala et al., 2011), indicating possible implicit learning of Western music categorizations due to years of exposure to Western music, in line with the findings of Brattico et al. (2009). However, an alternative explanation for the result is that the obtained MMNs were enhanced or elicited because some of the participants had formal music training and not merely due to the participants' implicit or passive exposure to Western music, since the only criterion for them was that they were not professional musicians. Additionally, in the absence of a musician group in the study, no conclusions of the role of explicit vs. implicit music exposure can be drawn. In a second study, school-aged children with music training elicited MMNs to minor chords in the context of major chords whereas children without music training did not (Virtala et al., 2012), suggesting that explicit music training can facilitate the pre-attentive neural processing of Western music chord types. It is, however, unclear, whether the absence of MMN to minor chords in the children without music training in this study was due to a smaller amount of implicit music exposure, smaller amount of explicit music training, or differences in brain maturation compared to the children with music training or the non-musician adults in Virtala et al., 2011. Importantly, our studies have not shown MMNs to inverted major chords in the context of (root form) major chords either in musicians or non-musicians, questioning whether the discrimination is relevant at least for participants without extensive levels of explicit music training.

Furthermore, even though MMN is associated with behavioral discrimination accuracy, i.e., a difference between sounds that is detectable in a listening task usually elicits an MMN response and vice versa, and the MMN amplitude size seems to correlate with the deviant sound detection accuracy (Amenedo & Escera, 2000; Näätänen, Schröger, Karakas, & Tervaniemi, 1993; Novitski, Tervaniemi, Huotilainen, & Näätänen, 2004; see also Horváth, Winkler, and Bendixen (2008)), this association has not been widely studied with music stimuli, nor in studies comparing musicians vs. non-musicians. It is possible that the superior auditory processing capabilities of musicians over non-musicians are more pronounced in attentive listening situations than in passive situations, where MMN is often recorded (Tervaniemi, Just, Koelsch, Widman, & Schröger, 2005).

One limitation regarding the most studies related to music sound processing in the brain is that they have used rather artificial stimuli composed of sinusoidal tones (this common restriction was pointed out by Koelsch and Mulder (2002)). Stimulation paradigms composed of sinusoidal tones lack the spectral richness of authentic music sounds and, thus, ecological validity. There is evidence that the presence of harmonics might facilitate sound processing in the early, pre-attentive level, as suggested by larger amplitudes and shorter latencies of ERPs to harmonic sounds vs. sinusoidal tones (MMN in Tervaniemi, Alho, Paavilainen, Sams, and Näätänen (1993), and Tervaniemi et al. (2000a), Tervaniemi, Schröger, Saher, and Näätänen (2000b); P3a in Novitski et al. (2004); P2 in Shahin, Roberts, Pantev, Trainor, and Ross (2005), and Shahin, Roberts, Pantev, Aziz, and Picton (2007)). Also behavioral detection might be more accurate for harmonic sounds when compared with sinusoidal tones (Tervaniemi et al., 2000a). Thus, the results obtained with paradigms using sinusoidal sounds, including the paradigm introduced by the authors, may give misleading information on the neural basis of authentic music sound categorizations and lead to underestimation of auditory processing capabilities of both musicians and non-musicians. Direct comparisons of the ERPs elicited by harmonically rich music sounds and sinusoidal sounds as well as their behavioral detection in musician and non-musician participants are thus needed to overcome this problem.

In the present study, we asked whether professional musicians and age-, gender- and education-matched non-musicians differentially discriminate Western music chord types neurally, in the level of pre-attentive MMN elicitation, and behaviorally, in a chord detection task. Furthermore, we asked whether the results are similar with chords composed of sinusoidal sounds vs. harmonically rich piano sounds. In addition, the effect of musicianship on the N1 amplitude was studied. N1 was chosen as an index of basic auditory processing, since its latency range is unlikely to overlap with MMN in the current paradigm (Näätänen & Picton., 1987). We examined how the MMN and N1 amplitudes and musicianship independently predicted the behavioral chord detection performance. In order to control for differences in general cognitive performance between musicians and non-musicians, suggested in prior studies (Schellenberg, 2006; Ho, Cheung, & Chan, 2003; Moreno et al., 2011; George & Coch, 2011), we assessed whether the groups performed equally well in psychological tests measuring memory, linguistic and visual skills, as well as processing speed and executive functions.

We expected that (1) musicians would outperform non-musicians in chord processing both neurally (larger MMN and N1 amplitudes) and behaviorally, and while both groups would discriminate major vs. minor chords, only musicians would discriminate inverted major chords from root major chords, (2) compared to sinusoidal sounds, harmonically rich music sounds would facilitate chord discrimination (larger MMN amplitudes and superior behavioral performance), especially in musicians, and (3) larger MMN and N1 amplitudes would predict superior behavioral chord detection independent of group.

2. Materials and methods

2.1. Participants

A total of 33 participants (17 musicians, 16 non-musicians) were recruited from local music academies and universities. A musician was defined as someone who was either currently a full-time student in a music academy or a professional musician with a music academy degree. A non-musician was defined as someone who had a maximum of 2 years of formal instrument practice. The data of three participants were excluded from further analysis, since two of the participants in the non-musician group had an extensive amount of music-related activities and one participant in the musician group reported suffering from continuing tinnitus.

Thus, data of 30 participants consisting of 16 musicians forming a “musician group” (7 males, mean age 23, age range 19–32) and 14 non-musicians forming a “non-musician group” (6 males, mean age 25, age range 19–34) were analyzed. According to their own report, all participants were right-handed and did not have current neurological or hearing-related problems or take any medication that would affect the central nervous system. All of the participants gave a written informed consent to participate in the study and received a participation fee (vouchers for cultural or exercise activities) after completing the study. This study received ethical approval of the University of Helsinki Review Board in Humanities and Social and Behavioral Sciences.

2.2. Background questionnaires

Background information was collected from participants with a general form and a music-related e-form. The general form included questions about age, gender, handedness and problems related to hearing, language, vision or basic motor functions. In addition, participants were asked to report their educational level. In the music background e-form, non-musicians were asked to report their music-related formal and informal hobbies and music listening preferences. For musicians, in addition to the aforementioned parts, the form included questions of their formal music education, achieved degrees, working situation, main and secondary instrument information including practice onset, years played and the amount of daily practice hours as well as music playing preferences. Both groups were asked to report whether they had absolute pitch.

Regarding the socioeconomical status of the two groups, all but one musician and all non-musicians had completed upper secondary school, and four of 16 musicians and five of 14 non-musicians had a bachelor's or master's degree. One-way ANOVA with three education levels (upper secondary school, bachelor's degree, and master's degree) demonstrated no statistically significant group difference, $F(1,31)=1.40$, $p>.10$. However, while six of the musicians were currently studying in a conservatory of music (upper secondary level), all other participants in musician group and all participants in non-musician group had completed or were enrolled in higher education (university) studies.

In musician group, the mean starting age of first instrument was 6 years (sd=2,5; range 3–12) and the overall duration of formal instrument training was 16 years (2,7; 12–21). The number of current daily practice hours for all instruments was 3,3 (1,2; 0,5–5). The current main instruments among the musicians were, in order of frequency (some mentioned two main instruments), piano and singing (for both $n=4$), violin (3), cello (1), contrabass (1), flute (1), oboe (1), bassoon (1) and saxophone (1). The prior main instruments, or current secondary instruments with at least 2 years of formal training, were, in order of frequency, piano ($n=7$), singing (5), guitar (acoustic and electric, 4), bass (acoustic and electric, 3), violin (2), drums (2) and harmonium (1). All of the musicians had ear training (solmization, sol-fa etc.) as a part of their music education for 8 years on average (3,4; 2–14). No one reported having absolute pitch. 13 of 16 reported playing mostly classical music as opposed to other music genres, while preferences for playing and listening were more varied in genre. 13 of 16 musicians reported playing mostly by using musical notation (as opposed to improvising or playing by ear).

In addition to instrument practice, 10 of 16 musicians had participated in music play school, 14 had attended a choir or a singing group, 15 had played in a band in or outside of school and 7 had taken dance classes. 15 of 16 reported listening to music on a regular basis on their free time. When asked about the personal importance of their music activities, all of the musicians rated the importance of their formal as well as informal music activities (listening to music, going dancing, going to concerts etc.) as quite or very important. In the non-musician group, 5 of 14 had participated in music play school, 3 had attended a choir, 4 had played in a band, 6 had taken dance classes, and 4 had had instrument practice (2 of them 1–2 years in childhood, 2 of them for some months two years ago). 9 of 14 reported listening to music on a regular basis on their free time. When asked about personal importance, 4 of 14 rated their formal music activities and 8 of 14 their informal music activities as quite or very important.

2.3. Psychological tests

In order to rule out differences in general cognitive abilities and performance profile between the two groups, the participants were presented with parts of the Wechsler Intelligence Scale (WAIS-III, subtests: Similarities, Symbol search, Digit span, and Block design, Wechsler, 1997a) and Wechsler Memory Scale (WMS-III, subtests: Logical memory I–II, Paired associates I–II and Faces I–II, Wechsler, 1997b) as well as the Trail-Making Test A and B. These tests measure cognitive abilities related to linguistic and visual reasoning as well as visuo-motor skills, working memory, linguistic and visual memory, executive functions, and processing speed.

2.4. Auditory stimulus material

The stimuli presented in the EEG experiment and the behavioral chord detection task were created by combining sounds with frequencies from C4 (middle C) to F#5 with durations of 250 ms for "Sinusoidal-250" and 650 ms for "Sinusoidal-650" and "Piano-650" paradigms to triad chords presented in Table 1. The stimuli in the "Sinusoidal-250" and "Sinusoidal-650" paradigms were constructed of sinusoidal mono sounds without any upper harmonics created and combined with Adobe Audition v 3.0. The stimuli in the "Piano-650" paradigm were constructed of Steinway Grand soft piano sounds from the McGill University Master Samples dvd collection (Opolko & Wapnick, 2006) and modified and combined with Adobe Audition v 3.0. The 250-ms chords were shaped 25 ms and 650-ms chords 10 ms from the beginning and end. All the chords were amplified so that their volume level would be the same for all stimuli in all paradigms. The chords in the "Piano-650" paradigm were additionally shaped 100 ms from the end in order to make them sound natural and smooth. The stimuli in the "Sinusoidal-250" paradigm were identical to the stimuli used in previous work of the authors (Virtala et al., 2011, 2012, 2013) in order to make the present study comparable with it. However, the stimulus duration of 250 ms appeared to be too short for the piano sounds: they did not sound natural piano-like sounds but, instead, were more "hammer-like". Thus, the duration of 650 ms was considered optimal for the piano stimuli: the sounds were clearly recognizable as piano sounds, but still not impractically long for the purposes of oddball paradigm. The stimuli in the "Sinusoidal-650" paradigm were identical to the "Sinusoidal-250" stimuli except for their duration of 650 ms. The duration was chosen based on the piano stimulus duration, in order to ensure that the possible differences in MMN responses between sinusoidal and piano paradigms would not be due to duration differences between the stimuli. The auditory stimuli were presented and the behavioral responses in the chord detection task recorded with the Presentation software v 16.0.

2.5. EEG experiment

The EEG experiment consisted of three auditory oddball paradigms presented under a non-attending condition in random order. The paradigms were called "Sinusoidal-250", "Sinusoidal-650" and "Piano-650" with identical stimulus types and probabilities introduced in Table 1. The stimulus types and paradigm are illustrated in Fig. 1. Each paradigm consisted of 906 stimuli (134 or 135 per deviant type) introduced in a pseudo-random order so that at least one standard preceded every deviant. The time from the beginning of the stimulus until the beginning of the next stimulus was 1000 ms in each paradigm. Duration of each paradigm was approximately 15 min.

Table 1
The stimuli and their probabilities in the experimental paradigms. The notes in the lower octave are marked with 'and in the higher octave with ".

Stimulus type	Chord name	Notes	Probability (%) EEG experiments	Probability (%) Chord detection task
Standard: Major			70	80
	C-major	C′-E′-G′	5.8	6.7
	D^b-major	D$^{b\prime}$-F′-A$^{b\prime}$	5.8	6.7
	D-major	D′-F#′-A′	5.8	6.7
	E^b-major	E$^{b\prime}$-G′-B$^{b\prime}$	5.8	6.7
	E-major	E′-G#′-B′	5.8	6.7
	F-major	F′-A′-C″	5.8	6.7
	F#-major	F#′-A#′-C#″	5.8	6.7
	G-major	G′-B′-D″	5.8	6.7
	A^b-major	A$^{b\prime}$-C″-E$^{b\prime\prime}$	5.8	6.7
	A-major	A′-C#″-E″	5.8	6.7
	B^b-major	B$^{b\prime}$-D″-F″	5.8	6.7
	B-major	B′-D#″-F#″	5.8	6.7
Deviant			30	20
Minor			15	20 or 0
	F-minor	F′-A$^{b\prime}$-C″	5	6.7 or 0
	F#-minor	F#′-A′-C#″	5	6.7 or 0
	G-minor	G′-B$^{b\prime}$-D″	5	6.7 or 0
Inverted major (2nd inversion)			15	0 or 20
	A-major (2nd inv.)	E′-A′-C#″	5	0 or 6.7
	B^b-major (2nd inv.)	F′-B$^{b\prime}$-D″	5	0 or 6.7
	B-major (2nd inv.)	F#′-B′-D#″	5	0 or 6.7

2.6. Behavioral deviant chord detection task

The deviant chord detection task consisted of four parts with different paradigms: Sinusoidal-650-Minor, Sinusoidal-650-Inverted, Piano-650-Minor and Piano-650-Inverted. Thus, in contrast with the EEG experiment, each paradigm included only one deviant type, either minor or inverted major chords. As in the EEG experiment, the sinusoidal and piano paradigms had identical stimulus types and probabilities, introduced in Fig. 1 and Table 1. Sinusoidal and piano paradigms were introduced in counter-balanced order, but the Minor paradigm always preceded the Inverted paradigm. The stimuli were presented every 2 s in a pseudo-random order so that at least one standard preceded every deviant. All parts of the task consisted of a teaching session with 60 stimuli (duration 2 min), followed by a testing session with 150 stimuli (duration 5 min). In the teaching session, the participants were asked to listen to the sounds and look at the computer screen in front of them. A red circle appeared on the screen immediately after a target sound (a deviant), and the participants were asked to try and learn to detect the target sounds. The identity of the sounds was left unknown to the participants, with only a description that the target sounds "have a different name in music". In the testing session, the participants were instructed to press a button during or immediately after each sound that was followed by a red circle in the teaching session.

2.7. Experimental procedure

The study was conducted in two separate sessions, first 2,5 h and the second 2 h in duration, separated by 8–54 days (mean 24 days). The EEG measurement with the three experimental paradigms was conducted during the first session. During the EEG experiment, the participant watched a self-chosen DVD movie without sounds and was told not to move or blink a lot and not to pay attention to the sounds. The total duration of the EEG recording was approximately 1 h 15 min. During the second visit, the participant completed the deviant chord detection task (duration approximately 45 min) and the psychological tests (duration approximately 1 h). Both during the EEG experiments and the behavioral chord detection task, the participant sat on a comfortable chair in a soundproof, electrically shielded chamber, while the experimental paradigms were introduced via headphones (Sony Dynamic Stereo Headphones, MDR-7506) with a sound level of ~65 dB SPL(a). In the end of the second session the participant received the participation fee.

2.8. EEG recording and analysis

The EEG was recorded continuously from 64 electrodes (headcap and amplifier: Biosemi ActiveTwo, mk1, BioSemi B. V., Amsterdam, The Netherlands) placed according to the international 10–20-system, with additional 5 external Ag/AgCl electrodes (right and left mastoid behind the ears, vertical and horizontal electro-oculogram below and next to participant's left eye, tip of the nose) with sampling rate of 512 Hz.

EEG was imported to the BESA analysis program (v 6.0, BESA GmbH, Gräfelfing, Germany), filtered 1–30 Hz (slope 12 dB/oct, zero phase) and re-referenced to the mean of the mastoid electrodes. Automatic eye artifact removal was conducted (v 6.0, BESA, Berg & Scherg, 1994). The data were divided to epochs (450 ms post-stimulus in sinusoidal-250 and 650 ms post-stimulus in sinusoidal-650 and piano-650 paradigms) with a pre-stimulus baseline of 100 ms, and averaged separately for each individual, stimulus type and electrode in each paradigm. All epochs with voltage changes exceeding $+/-120\ \mu V$ were omitted from further analysis. The mean number of accepted epochs in the paradigms was 356 (sd=13) out of 363 for standard stimuli and 132 (sd=5) out of 134 or 135 for each deviant stimuli. A baseline correction for −100–0 ms was applied for all epochs prior to statistical testing.

2.9. Statistical analyses

2.9.1. EEG data

For statistical testing of N1, mean amplitudes were calculated from 30-ms windows centered around the first clear negative peak on grand-average waveforms on Fz electrode, separately for each paradigm, due to possible differences in peak latency. The latency windows based on Fz were employed for all electrode sites used in the statistical analyses. A repeated measures analysis of variance (ANOVA-R) was employed for testing chord type (major, minor, and inverted major) and group differences as well as their interactions separately for each paradigm for N1. The differences between paradigms were not analyzed due to obvious acoustic differences that are likely to cause differences in the N1 due to their different spectral composition and rise times (Näätänen & Picton, 1987). A region of interest of 35 electrode sites F5, F3, F1, Fz, F2, F4, F6, Fc5, Fc3, Fc1, Fcz, Fc2, Fc4, Fc6, C5, C3, C1, Cz, C2, C4, C6, Cp5, Cp3, Cp1, Cpz, Cp2, Cp4, Cp6, P5, P3, P1, Pz, P2, P4 and P6 was employed to the ANOVA-R.

In order to test the MMN incidence in the two groups, three paradigms and two deviant chord types, a *t*-test of the group-average standard stimulus response vs. deviant stimulus response values was conducted for each data point in the MMN latency range 150–250 ms post-stimulus on Fz electrode, where MMN typically shows maximal amplitude (Kujala, Tervaniemi, & Schröger, 2007). However, large numbers of conducted *t*-tests increase the risk of obtaining false positive results. Furthermore, consecutive data points are not statistically independent of one another, and in order to assess the validity of the criterion for MMN incidence, the correlation of consecutive data points (autocorrelation) needs to be taken into account. The autocorrelation of the signal was calculated with MatLab's autocorrelation function, and, based on the criteria suggested by Guthrie and Buchwald (1991), sufficient criteria for MMN incidence was defined as 9 consecutive data points (a time interval of ~18 ms, autocorrelation 0.9 on average) reaching statistical significance ($p<.05$) in the MMN latency range. The incidence of MMN has been previously assessed by analyzing consecutive data points by, for example, Petermann et al. (2009), McGee, Kraus and Nicol (1997), and Bauer et al. (2009). The effect sizes of the *t*-tests were calculated using Cohen's d (function for MatLab see Hentschke and Stüttgen (2011)).

For further statistical testing, MMN amplitudes were calculated as mean amplitudes of 50-ms time windows for each participant, paradigm, deviant type and electrode location. The time windows were centered around the midpoints of the statistically significant time intervals described above, separately for each paradigm, due to possible differences in peak latency. ANOVA-R was employed for the same region of interest as in the N1 analyses, for testing paradigm (Sinusoidal-250, Sinusoidal-650, Piano-650), deviant type (minor chord, inverted major chord) and group differences as well as their interactions.

2.9.2. Behavioral data

The group differences in the psychological tests were analyzed with two-tailed independent sample's *t*-tests separately for each standardized subtest score. The performance in the behavioral chord detection task was quantified as hits-per-button-presses ratios individually for each participant in each part of the task. Since the proportion of deviant chords in each task was 20%, a hit-ratio above 20% indicated above-chance performance. The performance in both groups in the four parts of the task was compared to chance level with one-sample *t*-tests. The differences in performance between stimulus types (sinusoidal tones and piano sounds), deviant types (minor and inverted major) and groups as well as their interactions were analyzed with ANOVA-R.

In order to analyze the relationship between behavioral chord detection performance and N1 and MMN amplitudes, 2-tailed Pearson correlations were conducted over groups. Additionally, in order to take into account the effect of group, a step-wise linear regression analysis was conducted to predict behavioral detection performance with the N1 and MMN amplitudes (step 1) and musicianship as well as its interaction with the N1 and MMN amplitudes (step 2) as dependent variables. In the interaction analyses, continuous variables were mean-centered to reduce possible multicollinearity. Prior to regression analysis, homogeneity of variances was analyzed with Levene's tests. The results did not indicate differences in variance between the two groups.

For all the ANOVA-Rs, Greenhouse–Geisser correction was applied when sphericity could not be assumed. Statistically significant effects with more than two levels were further analyzed with Bonferroni-corrected pair-wise *t*-tests. ANOVA-R analyses were conducted in SPSS Statistics 21 (IBM).

3. Results

3.1. Chord processing: group and chord type differences

3.1.1. N1 and MMN amplitudes

The ERPs to all the stimuli in all the paradigms for the two groups are illustrated in Fig. 2. The mean amplitudes of N1 responses to each stimulus type and each paradigm in the two groups are listed in Table 2. In Sinusoidal-250 paradigm, N1 amplitude showed a statistically significant effect of stimulus type, $F(2, 56)=8.66$, $p<.01$, so that N1 was smaller to minor chords than to major chords ($p<.01$) or inverted major chords ($p<.05$). There was no statistically significant group difference, $F(1,28)=1.12$, $p>.10$. In Sinusoidal-650 paradigm, N1 amplitude showed a statistically significant effect of stimulus type, $F(2, 54)=6.69$, $p<.01$, so that N1 was smaller to minor chords than to major chords ($p<.01$). Additionally, there was a statistically significant group difference $F(1, 27)=4.43$, $p<.05$, indicating larger N1 amplitudes in musicians than non-musicians. In Piano-650 paradigm, there were no statistically significant differences in N1

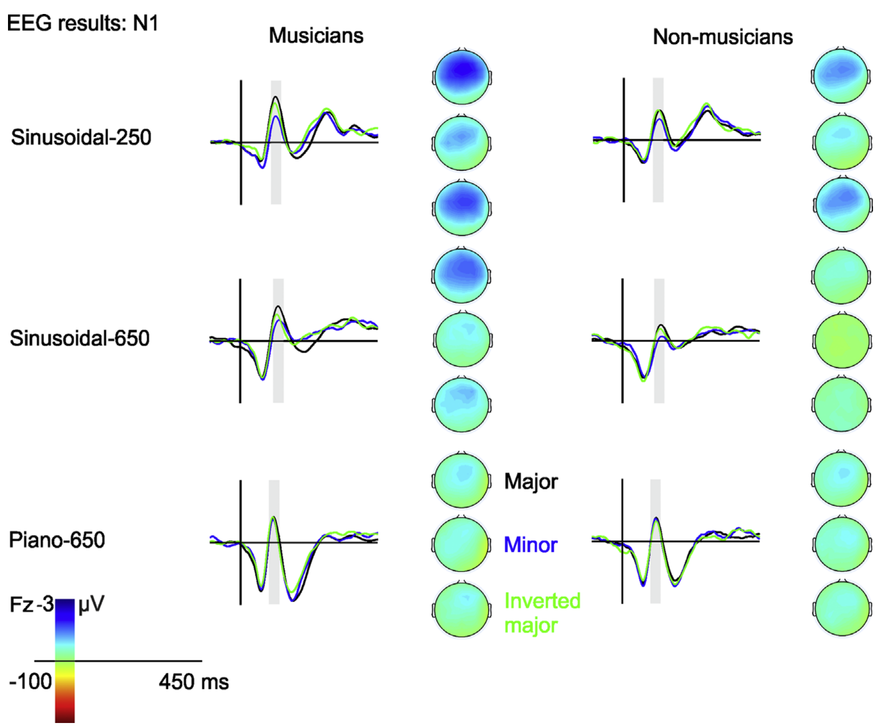

Fig. 2. Group-averaged ERP waveforms elicited by standard and deviant stimuli in the three experimental paradigms on Fz electrode. The latency windows where the N1 mean amplitudes were calculated for statistical analyses are marked with the gray-shaded bars. Head figures illustrate scalp distributions of N1 mean amplitudes.

Table 2
N1 mean amplitudes (standard deviation) from 30-ms windows on Fz electrode in μV in musician and non-musician groups for each paradigm and stimulus type, respectively. The latency windows where the mean amplitudes were calculated are shown in brackets.

	Major	Minor	Inverted major
Sinusoidal-250 (100–130 ms)			
Musicians	−1.99 (1.4)	−1.08 (1.0)	−1.63 (1.3)
Non-musicians	−1.25 (1.0)	−.87 (1.3)	−1.29 (1.3)
Sinusoidal-650 (110–140 ms)			
Musicians	−1.50 (1.2)	−.87 (1.0)	−1.08 (1.3)
Non-musicians	−.62 (.7)	−.08 (.8)	−.45 (1.1)
Piano-650 (95–125 ms)			
Musicians	−.90 (1.1)	−.74 (1.3)	−.90 (1.1)
Non-musicians	−.81 (.9)	−.77 (1.2)	−.81 (.9)

amplitude as a function of stimulus type, $F(1, 37)=.32$, $p>.10$ or group, $F(1, 28)=.00$, $p>.10$.

The MMN subtraction curves to both deviants in all the paradigms for the two groups are illustrated in Fig. 3. The mean amplitudes of MMN responses to each deviant and paradigm in the two groups are listed in Table 3. The latency range and amount of statistically significant consecutive data points and the effect size range on the *t*-tests is shown in Table 4. Both minor chords and inverted major chords elicited MMN-responses in Sinusoidal-250, Sinusoidal-650 and Piano-650 paradigms in the musician group. No MMN-responses were elicited in the non-musician group in any of the paradigms.

In ANOVA-R with all the three paradigms, there was a statistically significant group difference $F(1, 27)=15.31$, $p<.01$, so that MMNs were larger in the musician group than in the non-musician group. There was no statistically significant main effect of deviant type, $F(1, 27)=1.20$, $p>.10$.

In order to analyze the response patterns inside the groups more carefully, due to the main effect of group in the ANOVA-R and the absence of statistically significant MMNs in the non-

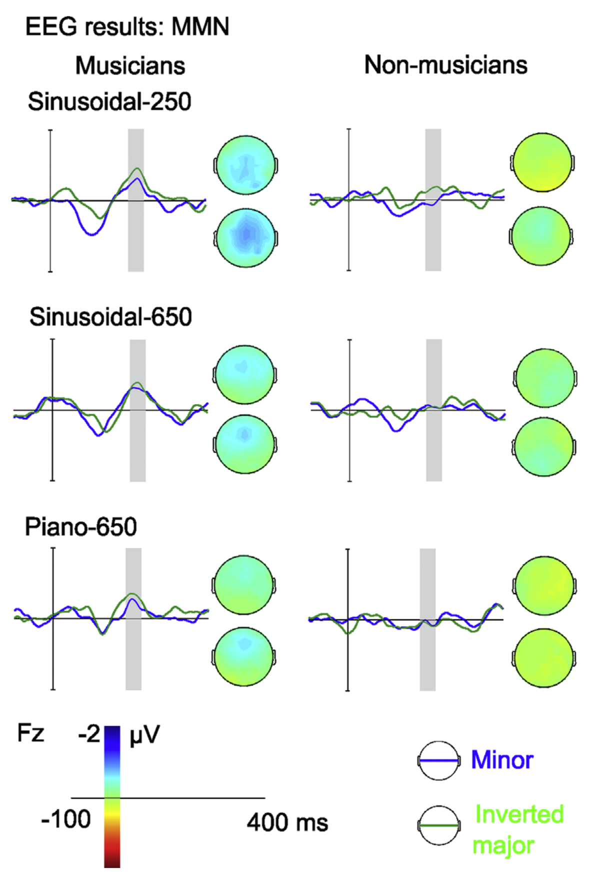

Fig. 3. Group-averaged MMN subtraction waveforms for the deviant-minus-standard stimuli in the three experimental paradigms on Fz electrode. The latency windows where the MMN mean amplitudes were calculated for statistical analyses are marked with the gray-shaded bars. Head figures illustrate scalp distributions of MMN mean amplitudes.

Table 3
MMN mean amplitudes (standard deviation) from 50-ms windows on Fz electrode in μV in musician and non-musician groups for each paradigm and deviant type, respectively. The latency windows where the mean amplitudes were calculated are shown in brackets.

	Sinusoidal-250 (195–245 ms)		Sinusoidal-650 (195–245 ms)		Piano-650 (180–230 ms)	
	Minor	Inverted major	Minor	Inverted major	Minor	Inverted major
Musicians	−.48 (.7)	−.76 (.7)	−.58 (.7)	−.64 (.6)	−.38 (.8)	−.62 (.5)
Non-musicians	.06 (.6)	−.30 (.6)	−.10 (.7)	−.09 (.5)	.11 (.7)	.12 (.6)

Table 4
Time interval and amount of consecutive data points showing statistically significant ($p<.05$) differences between standard and deviant responses in the MMN latency range 150–250 ms in musician group in each paradigm and deviant type, respectively.

	Minor vs. Major		Inverted major vs. Major	
	Time interval ms (data points *n*)	Cohen's d	Time interval ms (data points *n*)	Cohen's d
Sinusoidal-250	197–242 (24)	0.29–0.43	184–248 (34)	0.42–0.72
Sinusoidal-650	188–248 (32)	0.40–0.56	195–242 (25)	0.43–0.67
Piano-650	197–215 (10)	0.35–0.47	174–231 (30)	0.43–0.70

Table 5
Amounts of button presses (targets $n=30$) and hit-ratios in the chord detection task. Standard deviations are shown in brackets.

	Sinusoidal-650		Piano-650	
	Minor	Inverted major	Minor	Inverted major
Amount of button presses, *n*				
Musicians	24.6(7.0)	21.5(6.5)	25.6(6.5)	18.8(7.2)
Non-musicians	23.4(6.6)	21.1(4.6)	20.4(6.8)	21.4(8.6)
Hit-ratio				
Musicians	0.89(0.2)	0.71(0.3)	0.86(0.3)	0.59(0.2)
Non-musicians	0.54(0.2)	0.47(0.3)	0.48(0.3)	0.24(0.2)

musician group, separate ANOVA-Rs were conducted for the two groups. There were no statistically significant main effects of deviant type (in musician group $F(1, 14)=0.14$, $p>.10$, in non-musician group $F(1,13)=1.21$, $p>.10$) in either of the groups.

3.1.2. Behavioral chord detection

Table 5 shows the amount of button presses and hit-ratios in the chord detection task in the two groups. A similar amount of button presses in the groups, near the actual amount of targets in the paradigm, indicates that musicians and non-musicians made an equal and sufficient effort to perform in the task. The hit-ratios demonstrate that in the Piano-650-Inverted paradigm, the performance of the non-musician group was on chance level, while in other parts of the experiment, both groups performed above chance. This was confirmed by one-sample *t*-tests with test value of 0.2: the hit-ratios differed from 0.2 statistically significantly (in all $p<.01$) in all the other tasks in both groups, except for the Piano-650-Inverted in non-musician group ($p=.33$).

ANOVA-R of hit-ratios showed a statistically significant difference in performance between deviant types, $F(1, 23)=19.89$, $p<.001$, and groups, $F(1, 23)=46.88$, $p<.001$, so that performance was better in minor chord detection task than in inverted major chord detection task, and in musician group than in non-musician group.

3.2. Chord discrimination: differences between sinusoidal and piano sounds

MMN amplitude demonstrated no statistically significant main effects of paradigm (Sinusoidal-250, Sinusoidal-650, Piano-650) over groups, $F(2, 54)=1.85$, $p>.10$, or separately in musician group, $F(2, 28)=1.05$, $p>.10$, or non-musician group, $F(2,26)=2.03$, $p>.10$.

Hit-ratios in the behavioral chord detection task showed a statistically significant difference in performance between paradigms (Sinusoidal-650, Piano-650), $F(1, 23)=10.78$, $p<.01$, so that performance was better with sinusoidal than piano sounds. There were statistically significant interactions between paradigm and group, $F(1, 23)=5.99$, $p<.05$, and paradigm and deviant type, $F(1, 23)=5.42$, $p<.05$. Pair-wise *t*-testing of the interactions showed that performance was better with sinusoidal than piano sounds only in the non-musician group ($p<.001$) and only in the inverted major chord detection task ($p<.01$), while the musician group or the minor chord detection task demonstrated no differences between paradigms.

3.3. ERP amplitudes and behavioral chord detection

Since performance in all parts of the behavioral chord detection task strongly correlated with other parts (Sinusoidal-650-Minor with Piano-650-Minor, $r=.90$, Sinusoidal-650-Inverted with Piano 650-Inverted, $r=.67$, Piano-650-Minor with Piano-650-Inverted, $r=.68$, and Sinusoidal-650-Minor with Piano-650-Inverted, $r=.57$, in all $p<.01$), a combined performance score was calculated for overall behavioral performance by averaging the hit-ratios in the four parts of the task together. Similarly, as ERP amplitudes to minor chords vs. inverted major chords correlated with each other within the paradigms both for N1 (Minor-N1 with Inverted-N1 in Sinusoidal-650, $r=.67$, and in Piano-650, $r=.59$, in both $p<.01$) and MMN (minor-MMN with inverted major-MMN in Sinusoidal-650, $r=.47$, $p<.01$, and in Piano-650, $r=.49$, $p<.01$), combined variables N1-Sinusoidal, N1-Piano, MMN-Sinusoidal and MMN-Piano were calculated by averaging the N1s and MMNs to minor chords and inverted major chords on Fz electrode together.

Scatter plots illustrating the relationship of overall behavioral performance and N1 and MMN amplitudes to sinusoidal and piano sounds with correlation coefficients over groups are shown in Fig. 4. Larger (increasingly negative) MMN-Piano and N1-Sinusoidal amplitudes were associated with more accurate behavioral performance over groups. Similarly, in the regression analysis with MMN and N1 amplitudes, a larger (increasingly negative) MMN-Piano amplitude was associated with more accurate behavioral performance, $b=-.15$, $t=-2.22$, $p<.05$, while the relationship between N1-Sinusoidal and behavioral performance

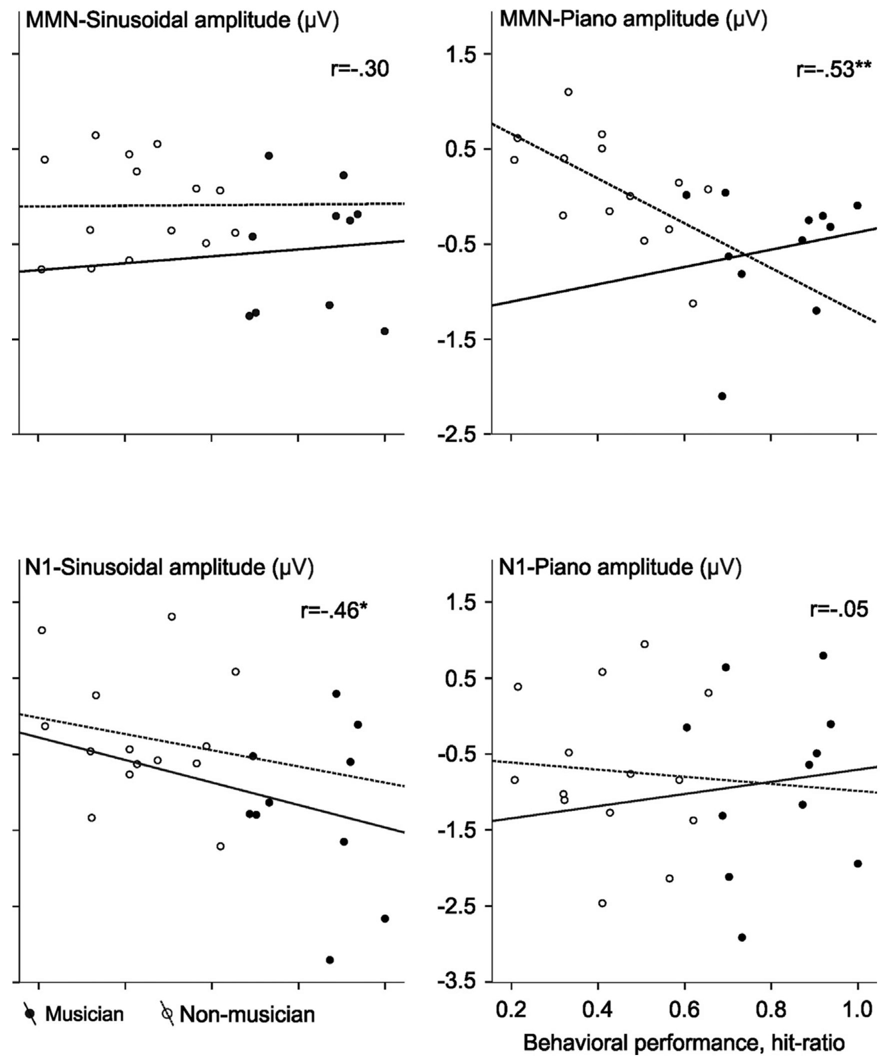

Fig. 4. Scatter plot images illustrating the overall behavioral detection performance (hit-rate, %) of individual musicians (black dots, solid line) and non-musicians (white dots, dashed line) as a function of N1 and MMN mean amplitudes in Sinusoidal-650 and Piano-650 paradigms. *R* values indicate 2-tailed Pearson correlations over groups.

Table 6
Group means of standardized subtest scores in the psychological tests, with standard deviations in brackets, and *t*-test results for 2-tailed independent samples comparisons of groups.

Subtest	Musician group	Non-musician group	*T*-test for equality of means
WMS-III			
Logical memory I	11.8 (0.6)	13.5 (0.5)	$t(26)=-2.06$, $p<.05$
Logical memory II	12.2 (0.5)	13.6 (0.5)	$t(26)=-1.09$, $p=.06$
Faces I	10.3 (0.7)	10.5 (0.9)	$t(26)=-0.18$, $p>.10$
Faces II	10.9 (0.6)	10.4 (0.7)	$t(26)=0.52$, $p>.10$
Paired associates I	12.9 (0.9)	14.8 (0.5)	$t(22)=-1.92$, $p=.07$
Paired associates II	12.8 (0.4)	13.3 (0.1)	$t(26)=-1.07$, $p>.10$
WAIS-III			
Similarities	11.5 (0.4)	13.5 (0.2)	$t(27)=-4.66$, $p<.001$
Digit span	13.8 (0.8)	11.9 (0.7)	$t(26)=1.81$, $p=.08$
Block design	12.4 (0.5)	11.9 (0.4)	$t(26)=.90$, $p>.10$
Symbol search	13.9 (0.9)	14.4 (0.5)	$t(23)=-.42$, $p>.10$
TrailMaking A, seconds	23.9 (1.8)	23.0 (2.9)	$t(27)=.26$, $p>.10$
TrailMaking B, seconds	46.4 (2.7)	52.4 (4.1)	$t(26)=-1.22$, $p>.10$

did not quite reach statistical significance, $b=-.09$, $t=-1.88$, $p=.08$. When musicianship and its interactions with N1 and MMN amplitudes were added to the model, the association between MMN-Piano amplitude and behavioral performance remained statistically significant, $b=-.16$, $t=-2.23$, $p<.05$, and, additionally, musicianship was associated with better behavioral performance, $b=0.36$, $t=4.76$, $p<.001$, and musicianship moderated the association between MMN-Piano and behavioral performance, $b=0.23$, $t=2.21$, $p<.05$. Group-wise correlations demonstrated that larger (increasingly negative) MMN-Piano amplitude was associated with more accurate behavioral performance in non-musician group, $r = -.53$, $p < .05$, but not in musician group, $r = .06$, $p > 10$. N1-Piano and MMN-Sinusoidal amplitudes were not statistically significantly associated with behavioral performance in either of the models (for all $p > .10$).

3.4. Psychological tests

The group-wise means of WAIS-III and WMS-III and Trail-Making A and B standardized subtest scores together with *t*-test results of group differences are demonstrated in Table 6. Statistically significant group differences were present in Logical memory I and Similarities, so that performance was better in non-musician than musician group.

4. Discussion

The present study investigated Western music chord categorizations in professional musicians and non-musicians both behaviorally and neurally. By presenting chords composed of both sinusoidal tones and harmonically rich music sounds in the experiment, we improved the ecological validity of the paradigm and thus the impact of the results. In line with our hypotheses, we found evidence of superior processing of Western music chords in musicians compared to non-musicians in three different and complementary ways. First, consistently in all three paradigms, MMNs were elicited by minor and inverted major chords in the context of root form major chords in musicians only. Second, N1 amplitudes were larger in musicians than non-musicians when 650-ms-long sinusoidal chords were used. Third, compared to non-musicians, musicians demonstrated superior discrimination of minor chords and inverted major chords from root form major chords in the behavioral chord detection task. In line with our hypotheses, major–minor categorization was evident in non-musicians behaviorally, but, contrastingly, minor chords did not elicit MMNs in non-musicians. However, a decrement of N1 amplitude in response to minor chords indicated possible early mode detection in both groups. Further, in line with our hypotheses, inverted major chords were mainly behaviorally discriminated by musicians only. In contrast with our hypotheses, no enhancements of MMN amplitudes or behavioral chord detection performance were seen with harmonically rich piano sounds compared to sinusoidal sounds. As we hypothesized, a correlation was found between behavioral detection accuracy and MMN amplitude, but only when the chords were presented with harmonically rich piano sounds and only in the non-musician group, where MMNs were not present in the group level. These findings are discussed in detail below.

4.1. Chord discrimination as evidenced by MMNs

In line with our hypotheses, in the professional musicians, MMN was elicited by both minor chords and inverted major chords in the context of root form major chords in all the three paradigms. The result is in line with a large body of evidence demonstrating superior pre-attentive neural processing of complex, music-related categorizations in musicians compared to non-musicians (Pantev et al., 1998, 2001b; Koelsch et al., 1999). However, the education level-, age- and gender-matched group of non-musicians did not obtain MMNs to either of the chords in any of the paradigms. This was in contrast with our hypotheses. In other studies, MMNs to minor chords in the context of major chords have been present in non-musicians (Tervaniemi et al., 2011), and even shown the same magnitude as the MMNs in musicians (Brattico et al., 2009). This discrepancy with the present results can be attributed to differences in paradigm complexity: while previous chord-MMN responses could be evoked by the acoustical content of the notes in the chords, this is not possible in the current paradigm. However, also the pioneering study of the authors reported MMNs to minor chords in non-musicians using a similar paradigm than is used here (Virtala et al., 2011). Still, as suggested in Section 1, varying amounts of music training in these non-musicians may explain the MMN elicitation in that study but not in the current study with very strictly controlled subject groups. The present result is consistent with another study of the authors, demonstrating major vs. minor chord categorization in musically trained 13-year-old children, but not in 13-year-old children without music training (Virtala et al., 2012). As the group difference in MMN elicitation is constant across the three paradigms in this study, we find this result highly reliable.

The musicians in the present study showed MMNs to inverted major chords without a difference in MMN amplitude between minor and inverted major chords. However, MMN to inverted major chords was absent in all prior study groups of the authors, including the 13-year-old children with musical training (Virtala et al., 2011, 2012). The result indicates that while some music-related changes are discriminated neurally even by non-musicians (like musical syntax violations in Koelsch, Gunter, Friederici, and Schröger (2000)), it seems that acquiring consistent neural representations of challenging music-related categorizations, like differentiation between root and inverted forms of the chord, may still require high levels of training and expertise in music.

4.2. N1 responses: early mode detection?

The larger N1 amplitude in musicians compared to non-musicians in the paradigm with long sinusoidal sounds in the present study is in line with our hypotheses as well as earlier findings (Pantev et al., 1998, 2001b; Shahin et al., 2003; Kaganovich et al., 2013), suggesting superior general auditory processing in musicians compared to non-musicians. However, the greater N1 amplitude in musicians compared to non-musicians was only present in one of the three paradigms in the study. In the future, in order to examine the profile of differences and similarities between musicians and non-musicians in general auditory processing of chord stimuli, a more systematic comparison of several ERP components in terms of both amplitude and latency should be conducted.

Surprisingly, the two paradigms with sinusoidal sounds also demonstrated smaller N1 amplitudes in response to minor chords compared to the standard major chords in both study groups. The paradigms with short sinusoidal chords also demonstrated smaller N1 amplitudes in response to minor chords compared to inverted major chords. These results seem to indicate that while the root major chords and inverted major chords elicit relatively similar neural patterns in N1 latency, the response elicited by minor chords differs from them. A possible explanation for this effect might be a low-level, MMN-like deviance detection process of minor mode chords in the context of major mode chords.

N1 may demonstrate smaller amplitudes to standard compared to deviant stimuli due to neural refractoriness effects, resulting in greater attenuation of the response to the often-repeated standard stimulus compared to the seldom-repeated deviant stimulus (see Näätänen and Picton (1987)). The present results of smaller N1 amplitudes to deviant than standard stimuli are thus in contrast with earlier findings. Also, in the paradigms of the present study, there was no single standard or deviant stimulus in acoustical terms, since all the frequencies in the deviants are already present in the standards, and each individual chord transposition, whether standard or deviant, has practically the same presentation probability in the paradigm. This seems to eliminate the possibility of neural refractoriness effects in the present paradigms.

However, minor and major chords differ in their degree of dissonance, since in Western music minor chords are considered slightly more dissonant than (root) major chords. Dissonant and consonant intervals elicit different neural activation patterns in the auditory system, demonstrated already in the auditory nerve (Tramo, Cariani, Delgutte, & Braida, 2001). N1 amplitude is known to be modulated by various stimulus properties, including the spectral composition, intensity and rise time (Näätänen & Picton, 1987). Based on the current evidence, it remains uncertain whether the N1 amplitude decrement to minor chords in the present study is attributable to, for example, harmonic properties or degree of dissonance in the minor compared to major chords. We take note that in our prior work (Virtala et al., 2013), newborn infants demonstrated mismatch responses to minor chords in the context of major chords, suggesting that major–minor categorization is rooted in the early levels and developmental stages of the auditory system.

4.3. Behavioral chord detection: effects of musicianship and chord type

In the behavioral chord detection task, in line with our hypotheses, musicians outperformed non-musicians. While the musicians performed partly at the ceiling of the task, the non-musicians performed at or merely above chance. These results together with the MMN results are in line with various previous studies showing superior auditory processing in musicians compared to non-musicians both behaviorally and neurally (Koelsch et al., 1999; Fujioka et al., 2004). Furthermore, even though MMN to both minor and inverted major chords was absent in the non-musicians in a non-attended listening situation, the non-musicians were able to learn to behaviorally discriminate the chord types to some extent after a short teaching period. Also, although the MMN amplitudes were similar to inverted major chords and minor chords in the EEG experiment, the minor chords were detected better than inverted major chords in the behavioral task by both musicians and non-musicians.

In the present study, the EEG was recorded in a passive listening situation, and the behavioral detection task was conducted afterwards in a separate session, without simultaneous EEG recording. Thus, the MMN responses to the chords were elicited in non-attentive conditions, and the behavioral responses were collected at a later time. This was done to avoid motor artefacts related to button presses and attention-related ERPs overlapping with the MMNs. Furthermore, various prior studies studying the associations of ERPs and behavioral discrimination accuracy have recorded the EEG in a passive listening situation, followed by a separate behavioral task (Amenedo & Escera, 2000; Novitski et al., 2004), and we wanted to make our results comparable with them. However, it is plausible that registering the ERPs and behavioral responses in separate sessions may compromise straightforward interpretations of the associations between MMN elicitation and behavioral detection of the deviant chord types. For example, since EEG was always recorded before the behavioral task, it is possible that the participants' detection accuracy was improved due to increasing familiarity with the stimulus material. Furthermore, a short teaching session preceded the behavioral task in the present study. Improvement in chord discrimination skills after short-term training has been demonstrated previously in non-musicians (Oechslin et al., 2012). Therefore, it is likely that an additional EEG recording during or after the behavioral task would have demonstrated different results than the first recording (see Seppänen, Hämäläinen, Pesonen, and Tervaniemi (2013)).

Additionally, while the advantage of the current paradigm lies in the carefully-controlled presentation probabilities of the chord transpositions, the deviant chord transpositions cover a more narrow frequency range than the standard chords. This is inevitable, when the probabilities of the individual tones (omitting the role of octave) are kept similar in the paradigm. Thus, by learning to exclude the chords with highest and lowest frequencies, the participants may have reached an above-chance performance level in the behavioral chord detection task. However, since this would not affect the differences in performance between paradigms, deviant types or groups, no marked limitations are set for the interpretation of the present results.

Also, it should be noted that a couple of the non-musicians in the present study had 1–2 years of instrument practice in the past. While they were clearly less experienced than professional musicians, prior studies have shown rapid plasticity and learning effects in children and adults after short-term music training (Hyde et al., 2009; Lappe et al., 2008). Thus, even a small amount of music practice, particularly in the recent past, should be taken into account when recruiting musically inexperienced participants. In the present study, however, majority of the non-musicians reported no formal music training, and the two non-musicians had their instrument practice more than 10 years ago.

4.4. Processing differences between sinusoidal and harmonically rich music sounds

The present study replicated the findings of the sinusoidal tone paradigms with harmonically rich music sounds, thus upgrading the ecological validity of the results. However, in contrast with our hypothesis, no differences in MMN amplitude were found between MMNs elicited by sinusoidal tone chords vs. piano sound chords. Earlier work has evidenced larger pitch-MMN amplitudes to harmonic sounds vs. sinusoidal tones, interpreted as facilitated auditory processing of pitch in harmonically rich stimulus material (Tervaniemi et al., 1993, 2000a).

In the behavioral chord detection task, performance was generally more accurate with chords composed of sinusoidal tones compared to piano sounds. However, since further tests showed that this effect was present only in the non-musicians and in the inverted major chord detection task, we find the result too inconsistent for drawing further conclusions, especially when taken together with the MMN result demonstrating no amplitude difference between sinusoidal tone chords and piano chords. Still, the present result is in contrast with our hypotheses and prior work showing facilitated behavioral detection of auditory change with harmonically rich sounds vs. sinusoidal sounds (Tervaniemi et al., 2000a, b).

In prior work, however, pitch discrimination of single tones with 1, 3, or 5 sinusoidal partials was under interest, while in the present study, chords at varying frequency levels were used. The current paradigm is much closer to real musical context than in prior studies, and examines complex music-related categorizations instead of simple frequency discrimination. Thus, it is possible that the difference between harmonically rich sounds and sinusoidal sounds in MMN amplitude and behavioral detection is lacking in the present study, because even the sinusoidal sounds in our paradigm are constructed to complex and music-related units.

Furthermore, while previous work has shown that especially complex and music-related stimuli demonstrate superior processing in musicians (Pantev et al., 1998, 2001b; Koelsch et al., 1999), the group differences in the present study were similar with sinusoidal vs. harmonically rich music sounds both neurally and behaviorally. Thus, in contrast with our hypothesis, the difference between musicians and non-musicians was not more pronounced with harmonically rich music sounds. Also, the most “musical” stimuli of the current paradigm, the harmonically rich piano sounds, showed no group differences in N1 amplitude in the present study, while the longer sinusoidal sounds did. Taken together, the present results do not provide evidence of facilitated neural or behavioral discrimination of harmonically rich music sounds compared to sinusoidal sounds in complex, music-related categorizations.

4.5. ERP amplitudes and behavioral detection

A correlation was found between larger (increasingly negative) MMN amplitude and more accurate overall performance in the behavioral detection task, however for the MMNs to the piano sounds only. When the effect of group was taken into account, the association remained significant, but it was moderated by group, so that the association was only significant among non-musicians. Previous studies have demonstrated a correlation between behavioral discrimination accuracy and MMN magnitude (Amenedo & Escera, 2000; Novitski et al., 2004). As visible in Fig. 4, non-musicians scoring high in the behavioral task tended to demonstrate negative values in the MMN latency, indicating MMN elicitation, while almost all musicians seemed to demonstrate MMNs and more accurate behavioral performance than non-musicians. Therefore, the lack of association between behavioral performance and MMN amplitude in musicians may be attributable to ceiling effects. Furthermore, no statistically significant correlation between the sinusoidal tone chords' MMN and behavioral detection was found. Taken together, the results may be interpreted as higher salience or relevance of piano sounds compared to sinusoidal sounds to the listener, resulting in greater consistency between behavioral performance and neural representations. On the other hand, also relatively small sample sizes and the absence of MMN in the non-musician group might explain the absence of a statistically significant correlation between MMNs to sinusoidal tone chords and behavioral performance. Therefore, no firm conclusions can be drawn based on the absence of statistical significance alone. While N1 amplitude in response to sinusoidal chords was also associated with behavioral performance over groups, the association did not remain significant in the regression analysis, controlling for MMN amplitudes and group. Therefore, the result is not discussed further.

4.6. Group differences in general cognitive abilities

The psychological tests demonstrated superior performance of the non-musician group compared to the musician group in two subtests, namely, Logical memory I of the WMS-III and Similarities of the WAIS-III. These subtests are related to linguistic skills (Wechsler, 1997a, b). We take note that a possible cause of the obtained group differences might be a difference in study field demands. While the musicians (had) studied in music academies and universities, the non-musicians specialized in several more literary study fields, e.g., social sciences and humanities. However, the result should be treated with caution due to small sample sizes and minor, non-significant differences in the duration and level of education between the study groups. We conclude that in light of these results, the superior auditory processing of music-related stimuli by musicians in the EEG and behavioral chord detection task cannot be explained by better general cognitive abilities of the musicians, or by superior skills in working memory, processing speed or executive functions.

5. Conclusions

As evidenced by MMN elicitation to minor and inverted major chords in the context of root form major chords in musicians only, greater N1 amplitudes in musicians compared to non-musicians, and superior performance of musicians compared to non-musicians in a chord detection task, the present study demonstrates beneficial effects of musicianship on Western music chord processing both behaviorally and neurally. These results are not attributable to superior general cognitive abilities of the musicians due to careful matching of the groups in the level of education. In contrast with prior work, these processes were not facilitated when the chords were composed of harmonically rich piano sounds compared to sinusoidal sounds. The qualitative and quantitative differences in the brain responses between musicians and non-musicians reveal a brain network effectively and automatically analyzing Western music chord modes and forms in trained musicians. While some music-related categorizations may be innate or implicitly learned, others may require extensive explicit training in order to be fully established in the auditory system.

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